TITLE

PARAMETRIC AND NONPARAMETRIC IDENTIFICATION OF SHELL AND TUBE HEAT EXCHANGER MATHEMATICAL MODEL

TATANG MULYANA

A Thesis submitted in
Fulfillment of the requirement for the award of the Degree of
Philosophy of Doctoral in Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

AUGUST 2014

DEDICATION

To my wife and my daughters
Mimih, Paramitha, Puterimely, Rofiya
For you is my little treasure

ACKNOWLEDGEMENT

All praise to ALLAH the Almighty. First and foremost Graceful and Merciful, for giving me the outmost strength and ability to made this humble effort a reality.

I would like to take this opportunity to express my gratitude to Prof Madya Dr Mohd Nor Bin Mohd Than and Dr Dirman Hanafi, my supervisor and co-supervisor for guidance and concerning the idea of the thesis to accomplish and improving the quality of this thesis.

My outmost thanks also go to my family who supported and encouraged me to persevere despite many difficulties, for their understanding through the duration of my studies.

Last but not least, thanks to all my friends and course mate for sharing the literature and invaluable assistance. Thanks to all the time support and encouragement in accomplishing this thesis.

ABSTRACT

Parametric and nonparametric models of a shell and tube heat exchanger are studied. Such models are very important because they provide information about controlling a system operation. Without the model, the control task would be difficult for tuning of controller. For many years, researchers have studied these models; however, their models are still less satisfactory since they are not in general form. This problem is caused by two key issues, namely, multiple unknown parameters and highly nonlinear structures. Energy balances have been set-up for condition of unknown parameters which involved, among others, temperature, flow rate, density and heat capacity. The identification process produces a dynamic model of the heat exchanger which is developed based on a lumped parameter system. The model developed is single input single output whereas input signal is hot water flow rate and the output is cold water temperature. The general form of the model obtained could have parametric model structures such as auto regressive with external input, average auto regressive moves with external input, output error or box-jenkins. The study in this thesis aims to solve the general form through parametric and nonparametric models which has been proposed as candidate models. Both candidate models have been implemented and tested by applying several data sets constructed in lab experiments. The first finding is the derivation of the dynamic model in the general form of the transfer function in s domain, and it has been proven that it has parametric model structure. The second finding is the first order without delay time transfer function of the nonparametric model where they have gain is 35.2^0C and time constant 7200s. These have proven to fulfill that the measured experimental data contains calculated error that is no than more 2%. The third finding is the parametric model obtained has proven that the measured experimental data contains calculated error level that is very satisfactory, i.e. less than 1%. This error has been determined based on the final prediction error for each model structure used. The best model has been chosen, i.e. bj31131. It has the smallest values of the loss function and final prediction error of 0.0023, and it has high values of the best fits, i.e. 96.84%. Parameter optimization has been calculated to determine minimization or maximization of functions which involved the parameter studied. It is used to find a set of design parameters that can in some way be defined as optimal. The first until the third findings are minor contribution while the parameter optimization has been a major contribution.

ABSTRAK

Model parametrik dan bukan parametrik sebuah penukar haba sel dan tiub telah dikaji. Model seperti ini amatlah sangat penting kerana ia menyediakan maklumat berkenaan dengan kawalan sebuah operasi system. Tanpa model ini, tugas kawalan akan menjadi sukar bagi penalaan pengawal. Selama bertahun-tahun, ramai penyelidik telah membuat kajian kepada model-model ini; walau bagaimanapun, model-model yang mereka perolehi masih kurang memuaskan kerana ianya tidak dalam bentuk am. Masalah ini wujud disebabkan oleh dua isu utama, iaitu pelbagai parameter tidak diketahui dan struktur yang sangat tak linear. Kesetimbangan tenaga telah ditubuhkan bagi keadaan pelbagai parameter tidak diketahui yang melibatkan, antara lain, seperti suhu, kadar aliran jisim, ketumpatan dan kapasiti haba. Proses pengenalpastian telah menghasilkan sebuah model dinamik penukar haba yang dibangunkan berdasarkan kepada sistem parameter tergumpal. Model yang telah dibangunkan ini mempunyai masukan dan keluaran tunggal dimana sebagai isyarat masukan adalah kadar aliran air panas dan sebagai isyarat keluaran adalah suhu air sejuk. Bentuk am daripada model yang diperolehi ternyata dapat dijadikan sehingga ianya mempunyai struktur model parametrik seperti auto regresif dengan masukan luar, purata auto bergerak regresif dengan masukan luar, ralat keluaran atau box-jenkins. Kajian didalam tesis ini bertujuan untuk menyelesaikan bentuk am tersebut melalui model parametrik dan bukan parametrik yang telah dicadangkan sebagai model calon. Kedua-dua model calon ini telah dilaksana dan diuji dengan menggunakan tiga buah set data dalam percubaan makmal. Sebagai dapatan pertama adalah model dinamik terhasil dalam bentuk am fungsi pindah dalam domain s, dan ianya telah terbukti mempunyai struktur model parametrik. Sebagai dapatan kedua adalah model nonparametrik dalam bentuk fungsi rangkap pindah perintah pertama tanpa kelewatan masa dimana ianya mempunyai gain sebesar 35.2^0C dan konstanta masa sebesar 7200 detik. Model ini telah terbukti memenuhi data percubaan dan mengandungi ralat kiraan yang besarnya tidak melebihi daripada 2%. Sebagai dapatan ketiga adalah model parametrik yang mana ianya telah terbukti memenuhi data percubaan dengan ralat yang mempunyai tahap yang sangat memuaskan, iaitu kurang daripada 1%. Ralat ini telah ditentukan berdasarkan ralat ramalan akhir bagi setiap struktur model yang digunakan. Model terbaik yang terpilih, iaitu bj31131, yang mana ianya mempunyai nilai bahagian kerugian dan ralat ramalan akhir yang paling kecil, iaitu 0.0023, dan juga mempunyai nilai sawan terbaik yang paling tinggi, iaitu 96.84%. Pengoptimuman parameter telah dikira untuk menentukan minimum atau maksimum fungsi-fungsi yang melibatkan parameter yang dikaji. Ianya digunakan untuk mencari satu set parameter rekabentuk yang dalam beberapa cara boleh ditakrifkan sebagai optimum. Penemuan yang pertama sehingga yang ketiga merupakan sumbangan kecil manakala pengoptimuman parameter merupakan sumbangan yang besar.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ARMAX	-	auto regressive moving average with exogenous input
ARX	-	auto regressive with exogenous input
BIBO	-	bounded input bounded output
BJ	-	box-jenkins
CFD	-	computational fluid dynamics
CUSUM	-	cumulative sum
D	-	drain
DAE	-	differential and algebraic equations
EE	-	equation error
FE	-	flow emitter
FOPDT	-	first order plus dead time
FPDD	-	first-principle data-driven
FPE	-	final prediction error
FT	-	flow transducer
HTC	-	heat transfer coefficients
I	-	integral
IMC	-	internal model control
LCV	-	level control valve
LF	-	loss function
LHP	-	left half plane
LT	-	level transmitter
MCHE	-	main cryogenic heat exchanger
MDF	-	matrix fraction description
MIMO	-	multi input multi output
MINLP	-	mixed integer non-linear programming

MSE	-	mean square error
ODE	-	ordinary differential equations
OE	-	output error
OELS	-	output error least square
P	-	proportional
P&ID	-	piping and instrumentation drawing
PB	-	proportional band
PDE	-	partial differential equations
PEM	-	prediction error method
PG	-	pressure gauge
PIA	-	pressure indicating alarm
PID	-	proportional-integral-derivative
PRBS	-	pseudo random binary sequence
PT	-	pressure transmitter
RTD	-	resistance temperature detector
SRIVM	-	simplified refined instrumental variable method
T	-	tank
TE	-	thermocouple element
TEMA	-	tubular exchanger manufacturers association
TG	-	temperature gauge
TIC	-	temperature indicating controller
TS	-	temperature sensor
TT	-	temperature transducer
TIT	-	temperature indicating transducer

CHAPTER 1

INTRODUCTION

1.1 Research Background

Introducing a mathematical model related to represent the actual system dynamics is very important to science and technology. Such models can be useful e.g. for simulation and prediction or for designation of digital control systems. Many industrial processes must be controlled in order to be run safely and efficiently. To design regulators, some type of model for the process is needed. The models can be of various types and degrees of sophistication. Sometimes it is sufficient to know the crossover frequency and the phase margin in a Bode plot. In other cases, such as the designation of an optimal controller, the designer will need a much more detailed model that can also describe the properties of the disturbances acting on the process.

In most application of signal processing in forecasting, the recorded data are filtered in some ways. In addition, a good design of the filter should reflect the properties of the signal. To describe such spectral properties, a model of the signal is needed. In many cases, the primary aim of modeling is to assist in the designing process. In other cases, the knowledge of a model can be the purpose itself. If the models can explain measured data satisfactorily then they might also be used to explain and understand the observed phenomena. However, sometimes this model is not easy to get especially when global representation system is required. Therefore, in order to solve the difficulties to get the dynamics model of process system, one can use system identification. The system identification is a technique to estimate the mathematical models of system dynamics based on data observed from the system (Knudsen, 2004; Ljung, 2011).

There are many usage of system identification. Some of those are for simulations and predictions for control and diagnosis in many fields such as engineering, economics, medicine, physiology, and geophysics. Therefore, it is rational to ask questions of where the model came from. There are currently three methods of system identification: white-box, gray-box, and black box (Aarts, 2012; Ljung, 2011). White box is an identification performed without the use of test data, based on the main principles only. Gray box is used both of prior knowledge process and experimental data for identification. Black box is an identification made exclusively from test data (Soderstrom, 2001).

Many researchers such as Nithya (2007), Sharma (2011), and Sivakumar (2013) are interested in identifying the dynamic model of heat exchanger. Modeling and control designing are not an easy task to do but very important because they are used in many industrial processes. Heat exchangers are used in the process of heating, cooling, and economizing processes. Heat exchanger is commonly in shell and tube type.

In this thesis, a parametric and nonparametric identification approach has been implemented to the shell and tube heat exchanger to produce the parametric and nonparametric models based on the few set of experimental data. In general, a parametric method can be characterized as a mapping from the recorded data to the estimated parameter vector while the nonparametric method is characterized by the property that the resulting model is a curve or function, which is not necessarily parameterized by a finite dimensional parameter vector (Soderstrom, 2001).

1.2 Problem Statement

The need for models of dynamic systems frequently arises in several engineering disciplines, for example in communication and control systems design. The emphasis in this work will be on parametric and nonparametric identification methods. For many years, researchers have studied about models of shell and tube heat exchanger. Their models have various coefficients. These facts can be seen in the Table 2.1. The models shown in this table are the models in which they are classified as the nonparametric model in first order system with time delay.

The disadvantage of this nonparametric model is the fact that it is not including offset. The offset means time needed to reach a heat exchanger temperature operation where the starting of the real heat exchanger operation is room temperature water at approximately 30℃. While the starting of the nonparametric model equals to 0℃. Alternatively, one can handle the offset problem by determining the parametric model. The main problem is, to determine the parametric model; there is a need to prove that the dynamic model has certain structure such as auto regressive with external input (ARX), average auto regressive moves with external input (ARMAX), output error (OE) or box-jenkins (BJ) structures. Therefore, the next step is to find a model that has best fits above 90% with the smallest values of loss function and final prediction error (FPE).

The best model of the parametric model depends on the order of polynomial equation. By choosing high order, it will result in highly nonlinear structure and increase possibility of best fits. But the resulted model is not practical because it will make the control task difficult. Therefore one must find a model that has the highest best fits; however, at the same time, it should not have highly nonlinear structure. In this case, the third order system is sufficiently high for the model system which is applied in the control design.

1.3 Benefit of the Study

In industrial process, heat exchanger is designed to transfer heat from one fluid to another. It has many different applications, especially in chemical process, air conditioning, and refrigeration. Since heat exchanger has a wide variety of applications and is commonly used in industry, control of the system is essential. A dynamic model may be created to allow the chemical engineer to optimize and control the heat exchanger.

By utilizing this model, predictions can be made to analyze how altering the independent variables of the system can change the outputs. There are many independent variables and considerations to account for in the model. If it is done correctly, accurate predictions can be made. Today, process engineers are responsible for many project activities, including conceptual design, revamp studies, and operational troubleshooting. Increasingly, the process simulator is an essential tool and become the central to these activities.

Process simulators are some very powerful tools for modeling all or parts of a process. While they are excellent for general purpose process modeling, it is the process engineer's responsibility to understand to what extent these tools can be applied, and how combining their application with more specialized tools might be appropriate. This choice is ultimately based on the business and technical objectives that want to be achieved. The heat exchanger models can enhance value derived from process simulation and provide more accurate results. These applications include conceptual designs of new plants, revamps of existing facilities, and operations support.

1.4 Objectives

These research objectives consist of:

1. To apply a parametric and nonparametric identification methods of shell and tube heat exchanger;
2. To collect and process a set data of the shell and tube heat exchanger;
3. To identify the parametric and nonparametric models of the shell and tube heat exchanger;
4. To validate the parametric and nonparametric models of the shell and tube heat exchanger.

1.5 Scope of the Study

The scopes of this study are:

1. A series of input-output datasets of the shell and tube heat exchanger are collected in experimental way. Three experimental datasets will be collected. The input signal is hot water flow rate inlet from tube side and the output signal is cold water temperature from shell side. These signals was measured using flow indicator to measure the hot water flow rate in m^3/hr and temperature indicating transmitter in ℃. The data was recorded in a graph paper at sampling time used of $7.2s$. The number of samples is 1000, so the duration times of each experimental data equals to

7200s. The real plant to get the data is Heat Exchanger QAD Model BDT 921 which has been installed in the Control Laboratory at the Universiti Tun Hussein Onn Malaysia. The data in the graph paper was then imported to workspace in MATLAB software and then displayed in the graph form. The details about plant description and how to undertake the data collection and processing can be seen in the Chapter 5.

2. The nonparametric identified method is applied to all data sampling collection to generate a nonparametric model. This method is determined based on the first-order plus dead time (FOPDT). Two models can be chosen namely, the first order transfer function without or with time delay, and the first or second order Pade-approximation. The best nonparametric model is chosen based on percentage of the error calculation between the model output and the data measured. The detailed about the candidate of the nonparametric model can be seen in the Chapter 3, especially in the Section 3.5. Furthermore, how the nonparametric identified method is applied can be seen in the Chapter 4, especially in the Section 4.3. The m-file program in the MATLAB software can be used to obtain the best nonparametric model.
3. The parametric identified method is applied based on a linear structure such as ARX, ARMAX, BJ, or OE. Before this method is implemented, one important thing is a need to prove that the dynamic model has parametric model structure. The dynamic model is formulated in an equation which has highly nonlinear structure and has many unknown parameters involved. This equation is generated from a description of the shell and tube heat exchanger process where it is assumed as a lumped parameter system. In this case, it is difficult to find a solution of the equation using numerical methods since many parameters involved are unknown values. The details to prove that the dynamic model has a linear structure can be seen in the Chapter 3, especially in the Section 3.4. The flowchart of the parametric identified method can be seen in the Chapter 4 (in the Section 4.2). The data applied in this method is required to be divided into two parts. The first half part is used to obtain the parameter estimation and the second half part is used to obtain the model validation.
4. The parameter estimation is determined through the order of polynomial equation in the parametric model structure. The polynomial equation of each parametric model structure includes ARX, ARMAX, BJ, or OE model structures can be seen in the Chapter 3 (Section 3.6). The validation parametric model is determined based on the loss of function (loss function), a final prediction error (FPE), and the appropriate percentage of fitting (best fits). The details about the validation theory can be seen in

the Chapter 4, especially in the Section 4.4. The m-file program or the toolbox in the MATLAB software can be used to produce the parameter estimation and the validation parametric model.

1.6 Research Methodology

The main goal in this thesis is to obtain parametric and nonparametric of shell and tube heat exchanger mathematical model. The model is produced by solving the dynamic model equations that has used parametric and nonparametric identification methods. One way to determine this model is based on the experimental data with implemented parametric and nonparametric identification methods. Based on the experimental data, it can be concluded that the nonparametric model is first order with time delay. In using parametric identification method, one needs to prove that the equations have a certain structure such as ARX, ARMAX, OE or BJ. In this thesis, it will be proven that the equation can have a parametric model structure.

The study in this thesis is aiming to solve the problem by proposing the parametric and nonparametric identification. Of especial importance, the thesis mainly conducts experiments to find the parametric and nonparametric models of the shell and tube heat exchanger. The nonparametric model has been found through first-order and second-order systems. Whilst the parametric model is developed with model structure, and it must be ARX, ARMAX, BJ, or OE. Based on these structures, one then needs to find the best model. The criteria to find the best model is based on the corresponding loss functions, final prediction error (FPE), and a percentage of fitting the model error (best fits) using MATLAB.

1.7 The Contributions of the Study

Thesis contributions are grouped into two parts, i.e. minor and major contributions as described herewith:

1. First contribution of the minor contribution is the derivation of dynamic model of shell and tube heat exchanger. The model is derived based on a lumped parameter

system where it could be more desirable and structured. The heat exchangers are divided into five regions of equal size in length with an assumption that, inside each element, shell and tube temperatures are uniform. For each section, energy balances can be set-up for shell and tube sides where the sides for inlet and outlet conditions involving temperature, mass flow rate, density and heat capacity. For each section, the set equations are given by Flores (2002). These equations can be seen in the Section 3.4 Chapter 3 equations (3.1) through (3.32). In this thesis, the set equations are developed to obtain a general form of a counter current shell and tube heat exchanger model in s domain. The general form is a single input single output (SISO) where the input variable is hot water flow rate inlet in tube side heat exchanger and the output variable is cold water temperature outlet in shell side heat exchanger. The general form obtained has been proven that it has a parametric model structure. These equations can be seen in equations (3.49) through (3.61). The finding of general form obtained to complete the study of the heat exchanger dynamic model. Therefore, this finding is the first contribution of this thesis.

2. Second contribution of the minor contribution is the nonparametric model obtained to solve the complicated equation of the dynamic model that has been derived. It has been previously verified that the equation is a nonparametric model. The verification can be seen in the equations (3.42) up to (3.48). The first order transfer function in the s domain is proposed as candidate model as it is proven to fulfill temperature output response of the heat exchanger experimental data, which has given satisfactory tolerable error. The candidate of the nonparametric model is shown in equations (3.62) up to (3.73) based on the experimental data. They are called dataexp1, dataexp2 and dataexp3 which have nonparametric model characteristics. These results can be seen in equation (6.3) for dataexp1, equation (6.4) for dataexp2, and equation (6.5) for dataexp3 in Chapter 6. The first order transfer function of the nonparametric model has proven to fulfill the measured experimental data, whilst its estimated error is decreasing to a zero level after 2600s. This result is the second contribution of this thesis to complete the study of the heat exchanger dynamic model. It is substantially different from the results obtained by many researchers as demonstrated in Table 2.1 in the Literature Review in Chapter 2.
3. The third contribution of the minor contribution is the parametric model obtained to solve for the complicated equation of the dynamic model. It is derived to be simpler and more structured as shown in equations (3.49) through (3.61) in Section 3.4 of

Chapter 3. Equation (3.49) is ARX model structure, equation (3.53) is ARMAX model structure, whilst equation (3.57) has OE model structure. Furthermore, equation (3.60) is BJ model structure. The candidate of the parametric model such as ARX, ARMAX, OE, and BJ, has been proven to fulfill the measured experimental data, and it has satisfactorily met certain criterion for parameter estimation and model validation. This criterion has been determined based on the best fits, loss function and FPE values for each model structure used. The best fits of all experimental data is more than 90%, the loss function and FPE are less than 0.0400. The resulted parametric model produces residuals that are within the confidence interval. The best model chosen is bj31131, it has the smallest value of loss function and FPE, i.e. 0.0023 and high best fits of 96.84%. Lastly, it has also been proven by parameter optimization through the calculation of an assessment of W_N.

4. Parameter optimization which has been as major contribution is determined to use minimization or maximization of functions which involved the parameter studied. It is used to find a set of design parameters that can in some way be defined as optimal. In a simple case this may be the minimization or maximization of some system characteristic that is dependent on its parameters. In a more advanced formulation the objective function to be minimized or maximized, may be subject to constraints in the form of equality constraints, inequality constraints and/or parameter bounds. An efficient and accurate solution to this problem is not only dependent on the size of the problem in terms of the number of constraints and design variables but also on characteristics of the objective function and constraints. This optimization is used to find the best or optimal solution to a problem. Steps involved in formulating an optimization problem: conversion of the problem into a mathematical model that abstracts all the essential elements, choosing a suitable optimization method for the problem, and obtaining the optimum solution. Unconstrained optimization has been used in this thesis. It finds a vector that is a local maximum or minimum to a scalar function. The term unconstrained means that no restriction is placed on the range of the vector. Good algorithms exist for solving this optimization problem; such algorithms typically involve the computation of a Full Eigen System and a Newton process applied to the secular equation. Such algorithms provide an accurate solution. However, it requires time proportional to several factorizations. Therefore, for large-scale problems a different approach is needed. Several approximation and heuristic strategies have been proposed in the literature. The maximum of percentages of fitting

and minimum of a final prediction error have indicated the best model for the previous models. It gives consistent parameter estimates only under rather restrictive conditions. Two different ways are given by modifying the method so that a consistent estimate could be obtained under less restrictive conditions. The modifications are minimization of the prediction error for other more detailed model structures and modification of the normal equations associated with the least squares estimate. A scalar measure has been used to assess the goodness of the model associated with the true parameter. It is denoted by assessment measure, where the dependence on the number of data is emphasized. The assessment measure must be minimized by this parameter. To determine it, Equations (4.96) and (4.98) in the Chapter 4 could be used. Both equations constitute the relationship between the loss function and the FPE through the assessment measure. Its simplified form is given as AIC is Akaike's information criterion. The result of the best parametric model could be used to calculate this assessment, and it is given in Table 6.15. It can be seen from this table that the minimum AIC is -2630.2722. Based on this result, it can be concluded that the best model which has parameter optimization is bj31131. This model has the smallest loss function value of 0.0023 and FPE of 0.0023. In addition to that, it has the highest best fits value of 96.84%. The other method to determine the parameter optimization of the heat and disturbance transfer functions data experimental which it is shown in Table 6.16 used the Equation (4.174) and (4.175) as introduced in the Chapter 4. The results are presented in Table 6.17. From these results could be observed that the best heat transfer function which it is reached is 237.5094 by dataexp3 bj31131. While the disturbance transfer function for all data experimental is very satisfying, i.e. zero.

1.8 Thesis Outline

Chapter 1 consists of research background and problem statement in which the reflection of heat exchanger model is introduced. This model is very important; it provides information about the nature and the characteristics of the heat exchanger system that is crucial for the investigation and forecast operational system. The objectives, scopes, benefit and contribution of this study are also elaborated here.

Chapter 2 consists of introduction, mathematical modeling and system identification, nonparametric identification, parametric identification, and summary. The difference between mathematical modeling and system identification will be reviewed related to this study. The system identification method includes parametric and nonparametric are reviewed from many papers to provide information and to gain the knowledge related to this study.

Chapter 3 consists of process description and candidate model of shell and tube heat exchanger. It includes the introduction, classification of heat exchangers, process description, dynamic model, nonparametric model, parametric model, and summary.

Chapter 4 consists of system identification and validation theory. It includes the introduction, system identification, validation theory, and summary.

Chapter 5 consists of data collection and processing data of heat exchanger. It includes the introduction, plant description, data collection, processing data, and summary. The counter current shell and tube used in this study is heat exchanger of QAD Model BDT 921.

Chapter 6 is system identification result and analysis. It includes the introduction, result, analysis and summary.

The last chapter is the conclusion and recommendation.

CHAPTER 2

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter consists of literature review related to mathematical modeling and system identification. The difference between the mathematical modeling approaches will be presented in Section 2.2. The system identification method, including the parametric and nonparametric models, is reviewed from many papers to provide information and to gain the knowledge related to this study. The nonparametric identification and parametric identification methods as the implementation to shell and tube heat exchanger from many researchers on journals and proceedings papers can be found in Sections 2.3 and 2.4. The last section is the summary of this chapter.

2.2 Mathematical Modeling Approach

Basically, there exist two types of applied knowledge or information in describing a system in terms of a mathematical model. The first information is the experience that experts have built, including the literature on the topic, and also the laws of physics. The other type of information is the system itself. Observations from the system and experiments on the system are the foundation for the description of the system and its properties. In principle, there are also two different approaches in constructing a mathematical model of a system. The first is

REFERENCES

Aarts, R.G.K.M. (2012).*System Identification and Parameter Estimation*, Faculty of Engineering Technology, University Twente.

Agashe S., Ghatol A., and Agashe S. (2006). Automation of Heat Exchanger using Neural Network.*International Journal of Applied Mathematics and Computer Sciences Volume 3 Number 4*.

Aghareed, M.T., M.A. El-Rifai, Y.A. El-Tawil and R.M. Abdel-Monen. (1991). A New Dynamic Model for Shell and Tube Heat Exchangers. *Energy Conservat. Manage., 32*: pp. 439-446.

Amlashi N. J. S., Shahsavari A., Vahidifar A., Nasirian M. (2013). Nonlinear System Identification of Laboratory Heat Exchanger.*International Journal of Electrical and Computer Engineering (IJECE), Vol.3, No.1*, pp. 118~128.

Andersen, K. K. (2001).*Stochastic Modelling of Energy Systems*, Technical University of Denmark: PhD Thesis.

Babu B.V. (2004).*Process Plant Simulation*, Oxford University Press.

Balan R.(2007). Applications of a Model Based Predictive Control to Heat Exchangers, *Proceedings of Mediterranean Conference on Control and Automation*, June 27-29, Athens – Greece.

Belinda, C.C.M. (2002).*Modeling of a hot water system drum and heat exchanger process control training system*, Universiti Teknologi Malaysia: Master Thesis.

Belinda, C.C.M. (2010). Modelling of a Hot Water Drum and Heat Exchanger Process Control Training System, *11th International Conference Control, Automation, Robotics and Vision*, Singapore.

Bendapudi, S., Braun, J. E., and Groll, E. A. (2004). Dynamic Modeling of Shell-and-Tube Heat-Exchangers: Moving Boundary vs. Finite Volume, *International Refrigeration and Air Conditioning Conference*. Paper 649.

Bittanti S. and Piroddi L. (1997). Nonlinear Identification and Control of a Heat Exchanger: A Neural Network Approach, *J. Franklin Inst. Vol. 334B, No. 1*.

Bohlin, T. (1995). Editorial: Special Issue on Grey Box Modelling, *International Journal of Adaptive Control and Signal Processing, Vol. 9*, pp. 461-464.

Bonivento C., et al. (2001). Predictive Control vs. PID Control of an Industrial Heat Exchanger, *Proceedings of 9th Mediterranean Conference on Control and Automation*, Dubrovnik – Croatia.

Carlos A. S. (2002).*Automated Continuous Process Control*, John Wiley & Sons, Inc., pp137-161.

Cheng T and Asada H.H. (2006). Nonlinear Observer Design for a Varying-Order Switched System with Application to Heat Exchangers.*American Control Conference*, Minneapolis, Minnesota, USA.

Czop P., Kost G., Sławik D., Wszołek G. (2011). Formulation and identification of First-Principle Data-Driven models, *Journal of Achievements in Materials and Manufacturing Engineering 44/2*,pp. 179-186.

Davidson A. G., Jachuck R. J., Tham M. T. and Ramshaw C. (1995). On the Dynamics and Control of a Polymer Film Compact Heat Exchanger, *Heat Recovery Systems & CHP, Vol. 15, No. 7*, pp. 609-617.

David, B. (2002). Design of Shell and Tube Heat Exchangers When the Fouling Depends on Local Temperature and Velocity, *Applied Thermal Eng., 22*, pp. 789-801.

De Nicolao G. (1997).*System Identification: Problems and perspectives*, Dipartimento di Informatica e Sistemistica, Universiti di Pavia, Via Ferrata 1, 27100 Pavia, Italy.

Dhakad, S. et al. (2013).An Intelligent Control Strategies Implemented on Heat Exchanger System: A Case Study, *International Journal of Emerging Technologies in Computational and Aplied Sciences (IJETCAS)*, pp. 195-200, 2013

Diaz G., Sen M., Yang K.T., McClain R.L.(2010). Dynamic prediction and control of heat exchanger using artificial neural networks, *International Journal of Heat and Mass Transfer 44*.

Ding, Z. (2010). Design and Simulation of Fuzzy Control System for Water Temperature of Heat Exchanger, *Proceeding of the 2nd International Conference on Computer and Automation Engineering (ICCAE), Vol. 4*.

Dirman H. and Abdulrahman A.A. (2011). Control Modes Comparison Results Focused on Real Heat Exchanger System Response, *International Journal of Integrated Engineering, Vol. 3 No. 3*.

Dostal P., Vojtesek J., and Bobal V. (2013). Adaptive LQ Control of a Shell and Tube Heat Exchanger, *International Journal of Mathematics and Computers in Simulation, Issue 5, Volume 7*.

Dougherty, D. and Cooper, D. (2003). A Practical Multiple Model Adaptive Strategy for Single-loop MPC, *Control Engineering Practice 11*, pp. 141-159.

Ekadewi,A.H. (2001). Pengaruh Penggunaan Baffle pada Shell and Tube Heat Exchanger, *Jurnal Teknik Mesin Volume 3 Nomor 2*, Fakultas Teknologi Industri, Universitas Kristen Petra.

Erkan, I. (2009). CDM Based Controller Design for Nonlinear Heat Exchanger Process, *Turk J Elec Eng & Comp Sci, Vol. 17, No. 2.*

Fazlur Rahman M.H.R. and Devanathan, R. (1994).Modelling a Dynamic Feedback Linearisation of a Heat Exchanger Model, *Proceedingsof IEEE International Conference on Control and applications, Vol. 3*, pp. 1801-1806.

Gewitz, A. (2005).*EKF-based parameter estimation for a lumped, single plate heat exchanger*, www.cespr.fsu.edu/people/myh/reu_ppt05.

Habobi, N. A. (2010). PC-Based Controller for Shell and Tube Heat Exchanger, *Iraqi Journal of Chemical and Petroleum Engineering, Vol. 11, No. 1*, pp. 47-53.

Halvorsen, H. P. (2012).*Control Theory with MathScript Examples*, Telemark University College, Norway.

Hasan M.M.F. et al. (2007).Modeling and simulation of main cryogenic heatexchanger in a base-load liquefied natural gas plant, *17th European Symposium on Computer Aided Process Engineering – ESCAPE17*, Elsevier B.V.

Hosseini R., Ghaffar A.H. and Soltani M. (2007). Experimental determination of shell side heat transfer coefficient and pressure drop for an oil cooler shell-and-tube heat exchanger with three different tube bundles, *Applied Thermal Engineering, Volume 27, Issues 5-6.*

Ingham J., Dunn I.J., Heinzle E., Prenosil J.E., Snape J.B. (2007).*Chemical Engineering Dynamics: An Introduction to Modeling and Computer Simulation*, Third, Completely.

Islamoglu Y. (2003). A new approach for the prediction of the heat transfer rate of the wire-on-tube type heat exchanger-use of an artificial neural network model, *Applied Thermal Engineering 23*.

Janczak A. (1993). Identification of Nonlinear Systems Using Neural Networks and Polynomial Models: A Block-Oriented Approach, LNCIS, Springer-Verlag Berlin Heidelberg, 2005

Johansson, Rofl, *System Modeling and Identification*, Prentice Hall, Englewood Cliffs, New Jersey.

Jorgensen, S. B. and Hangos, K. M. (1995). Grey-box modeling for identification and control, *SySID '94, volume 3*, pp. 231-236, IFAC.

Kang S.W. and Tseng S.C. (2007). Analysis of effectiveness and pressure drop in micro cross-flow heat exchanger, *Applied Thermal Engineering, Volume 27, Issues 5-6*.

Khare, Y. B. (2010). PID Control of Heat Exchanger System, *International Journal of Computer Applications, Vol. 8, No. 6.*

Kishore, D., Rao, S., Nityanandam, J. (2013). Experimental Studies and Controller Design of Shell and Tube Heat Exchanger using with and without Insert, *International Journal of Engineering Research and Applications (IJERA), Vol. 3, Issue 4*, pp.1126-1132.

Kokate, R. D. and Waghmare L. M. (2009). IMC-PID and Predictive Controller Design for a Shell and Tube Heat Exchanger, *Second International Conference on Emerging Trends in Engineering and Technology, ICETET09*.

Kokate, R. D. and Waghmare L. M. (2010).An IMC-DMC Control for Heat Exchanger, *International Journal of Computer Applications, Vol. 1, No. 26.*

Knudsen, M. (2004).*Experimental Modelling of Dynamics Systems*, Department of Control Engineering, Aalborg University.

Landau, I. D. (1990).*System Identification and Control Design using P.I.M. + Software*, Prentice Hall, Englewood Cliffs, New Jersey.

Leong K.C. and Toh K.C. (1998). Shell and Tube Heat Exchanger Design Software for Educational Applications,*Int. J. Engng Ed. Vol.14, No.3*.

Ljung, L. (1995).*System Identification*, Sweden, Department of electrical Engineering, Linkoping University.

Ljung, L. (1997).*Nonlinear Black-Box Modelling on System Identification*, Sweden, Department of electrical Engineering, Linkoping University.

Ljung, L. (1999).*System Identification: Theory for the User*, Prentice Hall, Upper Saddle River NJ.

Ljung, L. (2002). Prediction Error Estimation Methods, *Circuits Systems Signal Processing, Vol. 21, No. I*. pp. 11 - 21.

Ljung, L. (2008).*Perspectives on System Identification*, Division of Automatic Control, Linköping University Sweden.

Ljung, L. (2009).*Perspectives on System Identification*. Sweden, Report no.: LiTH-ISY-R-2900, Division of Automatic Control.

Ljung, L. (2010).*Approaches to Identification of Nonlinear Systems*, Division of Automatic Control, Linköping University Sweden.

Ljung, L.,Hjalmarsson H., Ohlsson H. (2011).*Four Encounters with System Identification*, Sweden, Division of Automatic Control, Linkoping University.

Ljung, L. (2011).*Approaches to Identification of Nonlinear System*, Sweden, Division of Automatic Control, Linkoping University.

Liu G. et al. (2005).Study on the Web Based Remote Monitoring and Controlling System for Heat Exchanger, *Proceedings of ISCIT2005*.

Luckow P.W. (2009).*Minimum Energy Design of Sea Water Heat Exchangers*, University of Maryland, College Park, Thesis: Master of Science.

Mahdi J.K. and Babak N.A. (2003).*NeuroPredictive Control of a Heat Exchanger: Comparison with Generalized Predictive Control*, IEEE.

Mahdi J.K. and Babak N.A. (2004). Neural Network Based Predictive Control of a Heat Exchanger Nonlinear Process, *Journal of Electrical & Electronics Engineering, Vol.4, No.2*, Istanbul University.

Markovska L., et al. (1995). Optimum Design of Shell and Tube Heat Exchanger, *Bulletin of the Chemists and Technologists of Macedonia, Vol.15, No.1*.

Mei Li, Chen Chen, and Wenlin Liu. (2009). Identification Based on MATLAB, *Proceedings of the 2009 International Workshop on Information Security and Application (IWISA 2009)*Qingdao, China.

Michael, C.G., Rotstein G.E., and Miccheietto S. (1998). Modeling and simulation of shell and tube heat exchangers under milk fouling. *AIChE J., 44*, pp. 959-971.

Mishra M. (2006). Transient behavior of crossflow heat exchangers due to perturbations in temperature and flow, *International Journal of Heat and Mass Transfer 49*,pp. 1083–1089.

Mishra M. (2008). Effect of temperature and flow nonuniformity on transient behavior of crossflow heat exchanger, *International Journal of Heat and Mass Transfer 51*,pp. 2583–2592.

Mukherjee R. (1998).*Effectively Design Shell and Tube Heat Exchangers*, Chemical Engineering Progress.

Navarro H.A and Gomez L.C.C. (2007). Effectiveness-NTU Computation with a Mathematical Model for Cross-Flow Heat Exchangers, *Brazilian Journal of Chemical Engineering Vol. 24, No. 04*, pp. 509 - 521.

Navarro H.A and Luben C.G. (2005). Technical Note: A new approach for thermal performance calculation of cross-flow heat exchangers, *International Journal of Heat and Mass Transfer 48*,pp. 3880–3888, 2005

Nithya, S., et al. (2007). Model Based Controller Design for Shell and Tube Heat Exchanger, *Sensors & Transducers Journal, Vol.84, Issue 10*, pp. 1677-1686.

Padhee, S. (2011).*Performance Evaluation of Different Conventional and Intelligent Controllers for Temperature Control of Shell and Tube Heat Exchanger,* Thapar University, India, Thesis: Master of Engineering.

Piotrowska E. and Chochowski C. (2012). Application of parametric identification methods for the analysis of the heatexchanger dynamics, *International Journal of Heat and Mass Transfer 55*,pp. 7109–7118.

Pongracz B., Szederkenyi G., Hangos K.M. (2002). The effect of algebraic equations on the stability of process systems modeled by differential algebraic equations, *Research Report SCL-003*.

Qiang X., Arthur Jutan A. (2002). Grey-box modeling and control of chemical processes, Pergamon, *Journal of Chemical Engineering Science 57*,pp. 1027 – 1039.

Qingchang, R. (1990).*Prediction Error Method for Identification of a Heat Exchanger*, Eindhoven University of Technology Research Reports, 1990

Radojkovic N., et al. (2003). Experimental Study on Thermal and Flow Process in Shell and Tube Heat Exchangers: influence of baffle cut on heat exchanger efficiency, *Facta Universitatis, Series: Mechanical Engineering Vol.1, No.10*.

Rajasekaran S. and Kannadasan T. (2010). A Simplified Predictive Control for a Shell and Tube Heat Exchanger, *International Journal of Engineering Science and Technology, Vol. 2 (12)*, pp. 7245-7251.

Rao K. S. (2007).*Analysis of Flow Maldistribution in Tubular Heat Exchangers by Fluent*, National Institute of Technology, Rourkela, Thesis: Master of Technology.

Ravagnani, M. A. S. S. and J. A. Caballero J.A. (2007). A MINLP Model for Rigorous Design of Shell and Tube Heat Exchangers using the TEMA Standards, *Chemical Engineering Research and Design, Trans IChemE, Part A.*

Raymond Chong and Shao Fen. (1995).*Manual Book of QAD Model BDT 921/M3; Boiler Drum and Heat Exchanger Process Control Training System*, Unpublished.
Renovfe, C. A., Vande W., Remy M. (2000). Neural Modeling and Control of a Heat Exchanger Based on SPSA Techniques, *Proceedings of the American Control Conference*, Chicago, Illinois.
Roetzel W. and Xuan Y. (1999).*Dynamic Behaviour of Heat Exchangers*, Witt Press, Computational Mechanics Publications.
Roffel B. and Betlem B. (2006).*Process Dynamic and Control: Modeling for Control and Prediction*, John Wiley & Sons, Ltd.
Saranya E. and Arulselvi S. (2013). Design and Simulation of Conventional and Intelligent Controllers for Temperature Control of Shell and Tube Heat Exchanger System, *International Journal of Recent Technology and Engineering (IJRTE), Vol. 2, Issue 3*
Shah R. K. and Sekulic D. P. (2003).*Fundamentals of Heat Exchanger Design*, John Wiley & Sons, Inc.
Sharma C., Gupta S., Kumar V. (2011). Modeling and Simulation of Heat Exchanger used in Soda Recovery, *Proceeding of the World Congress on Engineering (WCE), Vo. II*.
Singh V. (2009). Development of an Advanced Heat Exchanger Model for Steady State and Frosting Condition, University of Maryland, College Park, Thesis: Ph.D.
Sivakumar P., Prabhakaran D., Kannadasan T. (2012).Temperature Control of Shell and Tube Heat Exchanger by using Intelligent Controllers, *International Journal of Computer Applications, Vol. 59, No. 9*.
Sivakumar P., Prabhakaran D., Kannadasan T. (2013). Comaparative Analysis of Advanced Controllers in a Heat Exchanger, *American journal of Engineering Research (AJER), Vol.02, Issue 01*, pp. 01-06.
Sivaram A., Sainabha M., Ramkumar K. (2013).Parameter Identification and Control of a Shell and Tube Heat Exchanger, *International Journal of Engineering and Technology (IJET), Vol. 5, No 2*, pp. 1589-1593.
Soderstrom, T. and Stoica, P. (2001).*System Identification*, New York, Prentice Hall.
Sjöberg J.,Zhang Q., Ljung L. (1995).Nonlinear black-box modeling in system identification: a unified overview, *Journal of Automatica: Trends in System Identification, Volume 31*, *Issue 12*, pp. 1691–1724.
Smith C.A and Corripio A.B. (1985).*Principles and Practice of Automatic Process Control*, United-state: John Wiley & Sons.
Srinivasan A. and Lakshmi P. (2007). Wiener Model based Real-Time Identification and Control of Heat Exchanger Process, *J. Automation & Systems Engineering*.
Stenman, A. (1999).*Model on Demand: Algorithm, Analysis and Applications*, Linkoping University: Dissertations.
Szederkenyi G. (1998).*Model Based Fault Detection of Heat Exchangers*, Department of Applied Computer Science, University of Veszprem.
Tan K.C., Li Y. (2002). Grey-box model identification via evolutionary computing. *Control Engineering Practice 10/7*,pp. 673-684.
Thirumarimurugan M., Kannadasan T. and Ramasamy E. (2008).Performance Analysis of Shell and Tube Heat Exchanger Using Miscible System, *American Journal of Applied Sciences 5 (5)*, pp. 548-552.
Tomasz B., Piotr C. (2011). Estimation of feedwater heater parameters based on a grey-box approach, *Int. J. Appl. Math. Comput. Sci., Vol. 21, No. 4*, pp. 703–715.
Varshney K., Panigrahi P.K. (2005). Artificial neural network control of a heat exchanger in a closed flow air circuit, *Applied Soft Computing 5*.

Van den Hof P.M.J and Douma S.G. (2008).*An IV-based iterative linear regression algorithm with optimal output error properties: Technical report 09-018,*Delft Center for Systems and Control, Delft University of Technology.

Van den Hof P.M.J. (1989).Criterion Based Equivalence for Equation Error Models**,** *IEEE Transactions on Automatic Control, Vol.34, No.2*.

Vanden Hof P.M.J. (1994).Model Sets and Parameterizations for Identification of Multivariable Equation Error Models, *Automatica, Vol. 30, No. 3*, pp. 433-446.

Van Doren J.F.M, Douma S.G, Van den Hof P.M.J, Jansen J.D, Bosgra O.H. (2009). Identifiability: from qualitative analysis to model structure approximation, *15th IFAC Symposium on System Identification*, Saint-Malo, France.

Van Doren J.F.M, Douma S.G, Van den Hof P.M.J, Jansen J.D, Bosgra O.H. (2009).*Identification of parameters in large scale physical model structures: Technical report 10-022*, Delft Center for Systems and Control, Delft University of Technology.

Vasickaninova A. and Bakosova M. (2013). Application of H_2 and H_∞ Approaches to the Robust Controller Design for a Heat Exchanger, *Chemical Engineering Transactions, vol. 35*.

Venkatesan N., Sivakumaran N., Sivashanmuguham P. (2012). Experimental Study of Temperature Control using Soft Computing, *International Journal of Computer Applications, Vol. 52, No. 9*.

Vega A.P., Diaz G., Sen M., Yang K.T., McClain R.L. (2001). Heat Rate Predictions in Humid Air-Water Heat Exchangers using Correlations and Neural Networks, *Transaction of the ASME, Journal of Heat Transfer*.

Vega A.P., Sen M., Yang K.T., (2003). Simultaneous determination of in- and over-tube heat transfer correlations in heat exchangers by global regression, *International Journal of Heat and Mass Transfer 46*.

Vijaysai P. (2006).*Predictive Performance Assessment of Heat exchangers for Proactive Remediation*, IEEE.

Walter, D. (2000).*Controlling Shell and Tube Heat Exchanger*, First published in Hydrocarbon

Weyer E., Szederkenyi G., Hangos K. (2000). Grey box fault detection of heat exchangers, *Journal of Control Engineering Practice 8*, pp. 121-131.

Xia L, De Abreu-Garcia J. A., and Hartley T. (1991).*Modeling and Simulation of a Heat Exchanger*, IEEE.

Xie G.N, Wang Q.W., Zeng M. and Luo L.Q. (2007). Heat transfer analysis for shell-and-tube heat exchangers with experimental data by artificial neural networks approach, *Applied Thermal Engineering*.

Yutaka T. (1992). Equation error versus output error methods, *Ergonomics Journal, Vol. 35*, pp. 555 -564.

Yu Y.H and Sosna M.H. (2001). Modeling for Industrial Heat Exchanger Type Steam Reformer, *Korean J. Chem. Eng., 18(1)*, pp. 127-132.

Yu Zhao, Biao Huang, Hongye Sua, Jian Chua (2012). Prediction error method for identification of LPV models, *Journal of Process Control 22*,pp. 180-193.